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HIGH-ACCURACY LOCALIZATION OF MINIMUM IONIZING PARTICLES
USING THE CATHODE-INDUCED CHARGE CENTRE-OF-GRAVITY READ-OUT

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ABSTRACT

A measurement of the analogue centre of gravity of the induced charge distribution on cathode planes of multiwire proportional chambers allows the localization, in two dimensions, of the ionizing event. This paper describes the localization properties of such a method in the detection of minimum ionizing particles, and in particular the effect of ionization statistics and δ electrons. For a beam perpendicular to the chamber plane, accuracies of around 60 μm r.m.s. are obtained in the direction along the anode wires, and of 200 μm in the direction perpendicular to them. A separate measurement of the anodic drift-time allows improvement of the last measurement reducing it to 120 μm r.m.s. The multitrack coupling ambiguity is also discussed.

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1. INTRODUCTION

Localization of ionizing radiation in multiwire proportional chambers through the measurement of the distribution of charges induced on cathode strips, and subsequent calculation of their centre of gravity¹⁻³⁾, allows position accuracies approaching the limits set by the spatial extension of the ionization electrons⁴⁾ to be obtained. Because it requires the handling of a large amount of analogic information, the centre-of-gravity method has found so far a limited number of applications in cases where its bidimensional localization properties are essential, as in soft X-ray detection⁵⁻⁷⁾, or where the added wealth of information considerably improves the data quality, as in shower detectors^{8,9)}. However, with the rapid progress in microelectronics, relatively cheap and fast analogue-to-digital converters (ADC) are becoming available thus solving the major technical problem of the centre-of-gravity approach; large detection systems based on this principle can be envisaged that allow the space accuracy of present-day drift chamber systems to be attained with however the good resolution times of multiwire proportional chambers. Bidimensional read-out from a single detection layer, as given by the method, is very attractive also for use in detectors having cylindrical geometry, where alternative methods for obtaining the axial coordinate (delay lines, current division or small stereo angle between adjacent anode planes) offer a limited localization accuracy. A large detector of this kind is indeed already under construction¹⁰⁾.

The development work on the induced charge read-out has also resulted in a deepening of the understanding of several phenomena connected with the avalanche growth and distribution in proportional counters with as a result an improvement in some of the chamber's performances, as for example coordinate interpolation between wires in X-ray detection¹¹⁻¹⁷⁾ and removal of the right-left ambiguity in multiwire and drift chambers for charged particle detection¹⁸⁻¹⁹⁾.

As most of the previous work on the subject has been devoted to the detection of soft X-ray radiation, we have continued and extended our investigation to the information obtainable with the centre-of-gravity read-out when detecting minimum

ionizing particles, in various conditions of beam incidence, resolution time, and operational voltages. The results obtained so far are presented and analysed in the next sections.

2. EXPERIMENTAL SET-UP

The set-up used to study the localization properties of the induced charge read-out for minimum ionizing particles consisted in three aligned chambers, identical both in structure and in the associated electronics to the ones described in Ref. 12. Each chamber had an anode plane made of gold-plated tungsten wires, 15 μm in diameter and 2.54 mm apart (1/10 in., to match the output connector pitch), between two orthogonal cathode planes of Cu-Be wires 100 μm in diameter and 1.27 mm (1/20 in.) apart. The anode to cathode distance was 5 mm and the active surface of the chamber $100 \times 100 \text{ mm}^2$. All wires were positioned and soldered with good mechanical accuracy, so that the tolerance of each element in respect to a support frame reference was better than $\pm 15 \mu\text{m}$. The three chambers were mounted on individual turn-tables allowing both displacements and rotations with micrometer reading. Figure 1 shows the arrangement, as well as the definition of the reference system, with the beam along the z direction; the position of the central anode plane is characterized by the polar angles θ and Ω . The system has been operated at CERN on a non-separated test beam, with a momentum around 1.5 GeV/c; a set of scintillation counters provided both the time reference for the passage of the tracks and the geometrical definition of the beam.

As was found in previous work, the optimum cathode strip width for high-accuracy read-out corresponds to about one unit of anode-cathode distance¹²⁾; we have therefore merged together into individual measuring channels groups of four adjacent cathode wires. For convenience, the chamber was operated with grounded cathodes; for calibration and timing purposes, the over-all anodic signal was also recorded. For the set of these chambers, a total of 120 pulse-height measuring channels have been implemented on the cathode strips, three more channels being dedicated to the anode planes' signal. As far as the electronics is concerned,

we have used on each channel a simple charge preamplifier mounted on the chamber and having a sensitivity of about 250 mV/pC, a rise-time of 10 ns and a decay-time of 50 ns^{*)}; the amplified signals were then transmitted via coaxial cables to a CAMAC-based 10-bit charge-integrating ADC^{**)}. Operating the converter with a 50 ns gate, we obtained a full-scale sensitivity of around 1 pC, as referred to the pre-amplifier input (on the proportional chamber). The over-all electronics noise of the system in operational conditions was corresponding to about 2.5 ADC channels r.m.s.

The ADC gating functions could be realized either by a common signal initiated by the scintillation counters' coincidence, or chamber by chamber by the signal detected in the corresponding anode plane, suitably discriminated and shaped. The second method produced, as expected, the best results at short gating times (50 ns or below) as it maintains a close phasing with the cathode signals in the given chamber (the typical resolution time of a chamber of this kind is around 30 ns). It could only be used however in the case where a single hit was expected in each chamber.

In addition to the cathode and anode pulse heights, the anodic signal time, in respect to the scintillation counters, was also recorded for each chamber to provide additional information. A small on-line computer was used to organize the data acquisition and transfer to magnetic tape, and to perform sample analysis to control the performance of the chambers.

As a gas filling we have used an argon-isobutane-methylal mixture in the volume concentrations 67-30-3; the operational voltage for the chambers was situated between 2.8 and 3.0 kV. As will be discussed later, the best results in terms of accuracy have been obtained at high operational voltages. This was not however simply a result of the larger detected pulses (improving the signal-to-

*) Developed at CERN by J.C. Santiard and produced with a thick-film hybrid technique by CIT-Alcatel, France

**) Le Croy 12-channel ADC Type 2249A.

noise ratio). We definitely had an effect connected with the space-charge proportional gain saturation suppressing the influence of the large charge deposition asymmetries due to δ -rays (see Section 4). The presence of large space-charge effects is apparent from Fig. 2 which shows, as a function of anodic voltage, the normalized pulse height (signal per unit track length) for minimum ionizing particles and several values of the central chamber rotation angle θ (see Fig. 1). The increasing deviation from proportionality at large voltages and angles was already observed in similar conditions and interpreted to be a consequence of a reduced mutual influence of avalanches when they are spread over a larger section of the anode wire²⁰).

3. A SYSTEM CALIBRATION AND DATA HANDLING

The practical possibility of recording space accuracies in the 50 μm range depends mostly on an absolute knowledge of the strips' pulse-height distributions at the level of 1% or better, during data taking. Because of the large number of channels involved, we have preferred to use cheap elements with relatively large dispersions in conjunction with a careful calibration procedure, as against the possibility of individual hardware regulations. After several trials, the following calibration procedure was retained as providing a long-term reproducibility matching our needs. To begin with, all pedestal levels in the ADC (channel content when gating the unit without analogue input) were set around the same level, channel 20 out of 1024. Next, each individual pulse-height measuring channel (including the preamplifier, cable and ADC) was pulsed with the same reference signal obtained discharging a fixed capacitor from a constant voltage source; this reference signal, set at about the middle of the sensitivity scale, provided after pedestal subtraction the normalization factor between channels. Before and during the data acquisition runs, then, a common signal from a variable amplitude pulse generator was simultaneously applied to all channels by means of a bus strip capacitively coupled to the preamplifier's input on the printed circuit board. Of course, large relative dispersions were expected for the value of the

coupling capacitance that remains however fixed for a given channel. Increasing the generator pulse height in known steps (we have used a multiple calibrated attenuator, with 6 dB steps) for each channel a relative linearity curve could be obtained that, after pedestal subtraction and normalization to the previously described value, provided an absolute and zeroed charge-to-channel content calibration. As it appeared, six or seven amplitude values and a linear interpolation between adjacent steps were sufficient to guarantee the desired accuracy over several weeks of run. We should notice here that gain variations that uniformly affect the system (such as those due to moderate temperature changes) do not affect the determination of the centre-of-gravity of the pulse-height distribution.

Let us then denote by q_i the effective charge signal on strip S_i , as obtained from the raw data using the described calibration curves; we define the centre of gravity of a cluster of adjacent induced charges as the quantity:

$$\bar{s} = \frac{\sum (q_i - b) S_i}{Q}, \quad Q = \sum (q_i - b) \quad \text{for } q_i - b > 0, \quad (1)$$

where b is a bias level and the sum extends only to positive values of $q_i - b$ measured in a group of adjacent strips. A proper choice of the bias level allows reduction of the influence of pick-up and electronics noise in the centre-of-gravity determination and will be described later. A typical induced charge distribution on a cathode plane, as recorded for a single minimum ionizing track, is shown in Fig. 3 as well as the zero (pedestal) and bias levels. Negative amplitudes in the tail of the distribution, corresponding to ADC channel contents below the pedestal, are due to the unavoidable capacitive coupling in the proportional chamber between anode and cathode planes; we considered as significant for the analysis only positive amplitudes. In this definition, the even shown in Fig. 3 has a cluster size corresponding to five strips, of which three are above the bias level. It appeared that for single track events and in the y direction (strips perpendicular to the anode wires) around 13% of the events have this configuration, the largest majority having four significant strips; in the x direction, owing to the regularity in the pattern of facing wires, essentially all events had four significant strips.

Raw events were accepted for reconstruction under the following restrictions:

- none of the ADC channels was overflowing;
- the extremes of the cathode pulse-height distribution did not include the first or the last two strips in each plane, to avoid edge effects;
- the number of significant strips in each plane was smaller or equal to six, to eliminate multitrack events. At the particle flux at which we have been operating, the chance of having two tracks within the resolution time (50 to 100 nsec) close enough to escape the last selection in both planes was negligible. We also had the possibility in the analysis to reject events that provided avalanches in more than one adjacent wire, a kind of event clearly identified by the charge distribution along the x direction as will be discussed later.

For each accepted event, a straight line fit through the three pairs of computed centres of gravity provided the best estimate of the particle trajectory, and the variance of the residuals gave the positioning errors. As a rule, we measured the intrinsic dispersion of the set of three chambers operated in identical conditions and then, when changing the operational parameters only in the central one, we computed the new variance subtracting in a Gaussian sense the fixed contributions of two outer chambers.

As mentioned before, introduction of a bias level in the calculation of the centre of gravity [expression (1)] substantially improved the quality and the stability of the accuracy measurements. As is clear from Fig. 3, the effect of the subtraction is to eliminate the contribution of low content channels where noise can be predominant; on the other hand, choosing too high a bias level would result in a loss of information. We found the best results choosing a level proportional to the total charge measured in the analysed event on the significant strips for each plane:

$$b = k \sum q_i , \quad (2)$$

the value of k being determined experimentally as follows. Data obtained in running conditions where we expected the best localization accuracies (i.e. three identical chambers operated at high values of the anodic potential and normal to the beam) were repeatedly analysed for increasing values of the constant k , computing the position accuracy in each case. The points with error bars in Fig. 4 show the standard deviation of the position accuracy as a function of k ; the result is almost constant for values of k between 5×10^{-3} and 2.5×10^{-2} , while it deteriorates quickly outside those limits. In the figure we present also the results of a simplified computer simulation of the signal induction process that takes into account the discrete cathode strip width as well as the actual measured distributions, without (dashed curve) and with (full curve) inclusion of the experimentally measured electronics noise contribution (2.5 ADC channels r.m.s. as mentioned before). The agreement between calculation and measurement is rather good and confirms the correctness of our procedure. For the whole of the following analysis, we assumed a value of k of 0.025; the bias level indicated in Fig. 3 corresponds to this choice. A more detailed mathematical analysis of the induction process has been developed by Erskine²¹⁾.

4. EXPERIMENTAL RESULTS

4.1 Introduction

As was expected, the localization properties of a chamber using the induced charge read-out are better for the coordinate measured along the anode wires (the y direction) than for the perpendicular coordinate (the x direction). In the last case indeed the discrete structure of the anodes is bound to introduce a quantization effect in the distribution of induced charges; it was in fact for a long time admitted that at best one could obtain a localization corresponding to the spacing of the anode wires, thus implicitly assuming a symmetric distribution of each avalanche around the wires. Small right-left asymmetries were observed²⁾; however that could only be explained by a certain degree of localization of the avalanches around the wires; further work proved that this was indeed the case,

at least at moderate proportional gains^{12,13,15}) and that the x coordinate could be determined, for very localized energy depositions as given by soft X-rays, with almost the same accuracy as for the "continuous" y coordinate¹²). This is a direct outcome of the fact that, given the multiwire proportional chamber field structure, in most of the volume there is a unique association between the x coordinate of the photoelectric conversion point and the radial direction of approach of the ionization electrons to the wire (the exception being a small cylindrical region just around the anodes).

Charged particles however do not produce a single ionization centre, but instead a succession of clusters statistically distributed along the particles' trajectory. Ionization electrons therefore arrive at the anode at different times and with different directions of approach; at least one can hope to distinguish, from the measured distribution of the induced charges, the right and left side of the anode wires.

We will describe separately in what follows the measurements realized along the two directions in the central chamber; the two outside reference chambers were always operated under the conditions that guarantee the best localization accuracy.

4.2 Localization in the y direction, parallel to the anode wires

The three chambers were mounted initially with parallel anode wires; a rotation of the central chamber by an angle θ around x allowed the study of the effect of the spread along the anode wires of the avalanches produced by ionizing tracks. A very good check of the uniformity of response and correctness of calibration of the system is a plot of the reconstruction residuals (i.e. the difference between computed and measured coordinates) as a function of the coordinate itself. Figure 5 shows the distribution of the y residuals as a function of y in the central chamber, for a sample of events uniformly distributed over the active surface of the chamber. The distribution is consistently centred around zero, and its projection on the vertical axis (the usual accuracy distribution) has a r.m.s.

width around 45 μm , as already shown in Fig. 4. A defective channel or a wrong calibration, introducing a positioning error of the same order, would clearly appear as a discontinuity in the distribution.

The production in the primary collisions of heavily ionizing δ electrons is expected to smear the physical signal, thus implying a worsening of the localization accuracy. The effect is clearly demonstrated in Fig. 6 where, always for tracks perpendicular to the chamber plane ($\theta = 0$), the y residuals' distribution has been plotted for events providing an over-all charge deposit [the quantity Q in expression (1)] contained in three different regions of the energy loss spectrum. Events associated with large energy losses, region III, exhibit substantial tails at large residual values as compared with average (region II) and low (region I) energy losses. The effect is even more pronounced for inclined tracks, since in this case the asymmetry in the energy loss produced on the two sides of the anode plane by a δ electron has a large effect in the determination of the centre of gravity. This is well demonstrated in Fig. 7, where we have plotted the computed r.m.s. of the accuracy distribution for several values of the rotation angle θ ($\theta = 0^\circ$ meaning a beam perpendicular to the chamber plane). The accuracy has been computed for different regions of the energy-loss distribution, shown in the background of each plot^{*)}. At large angles, not only the average accuracy becomes worse but also the dependence on the energy deposit is increased.

We have observed that at high amplification space-charge effects can partially mask the quoted energy-loss dependent accuracy by suppressing the effects of high-density ionization produced by δ electrons. This effect is demonstrated by the two plots of Fig. 8, obtained in identical conditions except for the anodic voltage.

The ADC gating length (the time during which the induced charge distribution is sampled) is also important in defining the achievable accuracy; Fig. 9 shows

*) Notice that the horizontal amplitude scale is arbitrary and different in all plots; the relative values of the peak amplitudes were shown in Fig. 2 as a function of anodic potential and incidence angle.

the effect of reducing the gate from 100 ns (Fig. 7) to 50 ns; both the average and the extreme accuracies are improved for inclined tracks, as a direct result of restricting the measurement to the section of the ionizing trail closer to the anode (in our gas mixture, the average drift time is around 20 ns/mm). Short gating times and large anodic potentials are therefore useful to reduce the effects of the ionization statistics on the localization properties of the detector.

4.3 Localization in the x direction, perpendicular to the anode wires

The central chamber was rotated for this measurement by 90° around the z axis (see Fig. 1), to keep the good beam localization provided by the two outer reference chambers. As expected and for the reasons discussed in the Introduction, the localization properties along x are strongly dominated by the discrete anode wire spacing. Figure 10 shows the measured centre of gravity in the x direction (vertical axis), as a function of the beam real position as given by the reference chambers (horizontal axis) for a uniform irradiation over a section including two anode wires. The clustering effect around the anodes' position is clear, although one can distinguish a certain amount of interpolation events due to charge sharing between adjacent wires, and a moderate slope of the clustering due to the right-left effect. This is better seen in a projection of the scatter plot on the vertical axis, given in Fig. 11: the two peaks correspond to tracks crossing the anode plane respectively at the right and left of a wire. The small overlap is due to tracks crossing the anode-wire region; δ -ray production and electron diffusion obviously slightly smear the right-left separation at the boundary.

For tracks perpendicular to the chamber plane, only a small number of events result in charge sharing (mainly because of the finite beam divergency) but the effect is relevant at larger incident angle. Figure 12 shows, for example, the correlation between the measured and the real coordinate in the x direction, for a chamber rotation of 12° ; at increasingly large angles all tracks produce charge sharing and the quantizing effect of the anode wires gradually disappears. This effect was already observed and analysed in detail in previous work³⁾.

A closer look at Fig. 10 shows that the distribution of the centre of gravity has a small slope on each side of the middle, thus suggesting a certain amount of localization between the wires. We have therefore used the function correlating the real and measured values of the coordinate x as measured with soft X-rays¹²⁾ to deconvolute the clusters; Figs. 13a and b show, respectively, the correlation between real and measured coordinates before and after the deconvolution. Owing to statistical fluctuations in the energy deposit, however, the positioning accuracy for charged particles in the x direction is not as good as the one that could be obtained with X-rays. Moreover, the compression of the centres of gravity resulting from the discrete positioning of the anodes emphasizes the errors due to small non-linearities and calibration errors in the pulse-height measuring channels; at best, we have obtained a positioning error of 200 μm r.m.s.

This result can, however, be substantially improved making use of the measured drift-time to the anodes as mentioned before. Figure 14 shows a scatter plot of the measured drift-time on the anode wires as a function of the real coordinate (as given by the collimating chambers). The analysis procedure is then the following: a cut in the centre-of-gravity distribution (like the one shown in Fig. 11) separates tracks crossing the chamber on the two sides of the anode wires, and the x coordinate is obtained adding to the actual wire position a quantity

$$\Delta x = \pm w(t - t_0) \quad (3)$$

where $(t - t_0)$ is the measured drift-time and w the electron drift velocity. In the gas mixture we have used, the drift velocity is almost independent of the electric field, as demonstrated in previous work on drift chambers²⁰⁾, and has a value of around 5.2 $\text{cm } \mu\text{s}^{-1}$. The sign of expression (3) is of course chosen according to the side of the crossing. The distribution of the residuals measured using this procedure in the central chamber is shown in Fig. 15 having a standard deviation of 125 μm ; this is comparable with the value obtained in high-accuracy drift chambers for tracks close to the anode wires, where primary ionization statistics dominates the localization properties of the detector^{20, 4)}.

4.4 Double track ambiguity

In the induced charge read-out method the two coordinates in a plane are measured independently and therefore the coupling is unique only in the case of single track events. However, the strict correlation that exists between the total charge measured on the two cathodes, coupled with the large dispersion in the energy loss of the individual events due to Landau fluctuations, allows in many cases a correct pairing of coordinates, as already suggested by the authors of Ref. 3. Figure 16 shows indeed the dispersion of the measured ratio of total charge detected on the two cathode planes, Q_y/Q_x , as a function of Q_y . The dispersion is contained within 2 to 4% for most of the events, while it increases strongly in the tail of the large energy losses because of the asymmetric contribution of the δ -rays. Being limited in the total beam flux, we could not obtain a large enough sample of multiple tracks to check directly the efficiency of coupling. However, using the measured dispersions for single tracks we have computed the expected multitrack coupling efficiency using a Monte-Carlo generation of multiple events, each with the appropriate amplitude dispersion. The results show that in 95% of the cases the coordinates of two-tracks events can be correctly paired, as far as they are sufficiently separated in space to induce distinct charge distributions on both cathode planes. As from Fig. 3, this minimum distance corresponds to 5 strip widths (or 25 mm) in both directions.

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Figure captions

- Fig. 1 : The experimental arrangement of three identical chambers aligned in a medium-energy beam. The central detector can be rotated around both x and y to study the angular dependence of performances.
- Fig. 2 : Most probable detected pulse-height for minimum ionizing particles in the central chamber, as a function of anodic voltage and for several values of the rotation angle θ (see Fig. 1). The measured pulse heights have been normalized to a unit track length; space charge gain saturation is very large for small angles of incidence and large voltages.
- Fig. 3 : An example of measured pulse-height distribution on the cathode strips. Five adjacent channels record an induced charge above zero; the choice of the bias level is discussed in the text; see also the next figure.
- Fig. 4 : Dependence of the reconstructed position accuracy on the choice of the bias level constant k [see expression (2)]. Points with error bars represent the measured values, while the curves are the result of a model calculation that does not (broken line) or does (full line) include the electronic noise contribution.
- Fig. 5 : Experimental distribution of the residuals in the y direction, for a uniform irradiation of the chamber. The vertical dispersion has a FWHM around 100 μm , and its uniformity along the horizontal axis (the y coordinate) is a check of the consistency of the amplitude calibration procedure.
- Fig. 6 : Dependence of the residuals' distribution on the energy loss, measured for tracks perpendicular to the middle chamber along the y direction. Residuals have been plotted in (a) for three different regions of energy loss, which are shown in (b). The large tailing effect introduced by δ electrons is clear.

- Fig. 7 : Dependence of the measured localization accuracy along the y direction on the actual energy loss, for several angles of incidence of the beam. The accuracy is given by the points with error bars, computed for the slice in energy loss shown in the background. Notice that the horizontal amplitude scale is arbitrary and different for each angular setting; relative values of the actual peak amplitude were given in Fig. 2 as a function of angle and anodic voltage. Analogue gating length is 100 nsec.
- Fig. 8 : The same measurement as in the previous figure, for normal tracks at two values of the anodic potential. Space-charge saturation effects clearly suppress the δ electrons' contribution at large energy losses.
- Fig. 9 : Measured dependence of accuracy on pulse height and incidence angle, for a 50 ns analogue gating. Comparison with Fig. 7 shows the gain in accuracy resulting from the electronic selection of a shorter segment of the energy deposit.
- Fig. 10 : Correlation between the true (horizontal) and measured coordinate along the x direction, for a uniform irradiation perpendicular to the chamber. The quantizing effect of the anode wires on the centre of gravity is apparent.
- Fig. 11 : Projection of the scatter plot of the previous figure on the vertical axis, showing clearly the right-left separation as two partially overlapping peaks. The uniform background is due to tracks being at small angle with the perpendicular to the wires, and producing coordinate interpolation due to charge sharing.
- Fig. 12 : Same as for Fig. 10, for a small (12°) incidence angle. Coordinate interpolation is more pronounced.
- Fig. 13 : Deconvolution of the centre-of-gravity distribution using an experimentally-determined correlation function. The original distribution is shown in (a), and the deconvoluted or linearized one in (b). Notice the inversion of the horizontal and vertical axes as compared with Fig. 12. The resulting accuracy in the x direction has a standard deviation of about 200 μm (for 2.54 mm anode wire spacing).

Fig. 14 : Correlation between the measured drift-time on the anode plane (vertical axis) and the real track position along the x direction. The anode wire position corresponds to the lower edges.

Fig. 15 : Combining the right-left identification given by the centre-of-gravity read-out with the drift-time measurement, one can obtain an accuracy distribution in the x direction (perpendicular to the anode wires) having a standard deviation of 120 μ m.

Fig. 16 : Standard deviation of the ratio of measured total pulse heights on the two cathode planes, Q_y/Q_x , as a function of Q_y (points with error bars). The background histogram represents the Q_y distribution itself. The small value of the dispersion in the ratio allows in most cases an ambiguity-free correlation of the measured x and y co-ordinates in the case of multitrack events.

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